

## Pattern of Phases From the TeV BPM Using the Echotek Board

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### Abstract

This note explains the pattern of phases observed when the TeV BPM signals are processed with the modified recycler Echotek board. It also explains the bistable values for position and intensity which were discussed in Beams-doc-1059.

## 1 Introduction

To illustrate the effect, I have used some data taken on March 5, 2004, using the modified recycler Echotek board on BPM HA15. Figure 1 shows phases of the signals on the 4 cables. The phase is defined as the argument of the complex number (I,Q), where I and Q were read from the data logger. The data are discussed in more detail in Beams-doc-1062.

The critical observations is that, on each cable, the phase has 5 allowed values, separated from its neighbors by  $1/7$  of  $2\pi$ ; remember that the cut line at phases of  $\pm\pi$  is an artifact of the presentation so the points at the bottom of the plots are contiguous with those on the top. The pattern of which value follows which is not important — it is an artifact of the timing of the 15 Hz data logger. The allowed values differ from cable to cable, which represents true phase differences between the signals

## 2 A Toy Model

The first job is to explain why there are 5 stable values. Figure 2 has some plots from a toy model which will help explain this. In this toy model, times and frequencies are expressed in units in which the RF frequency  $f_{RF} = 1$ . The top plot in Figure 2 shows 10 periods of a sine wave with the RF frequency. The next plot shows the histogram of the waveform when it is digitized using a sampling frequency of  $7/5 f_{RF}$ . In this model, the sampling occurs at the leading edge of each period of the sampling clock. The sampled waveform repeats after seven measurements, which corresponds to 5 RF periods.

The Echotek boards down convert the data at the RF frequency. The math corresponding to this is,

$$(I, Q) = \sum_n e^{-i\omega_{RF} t_n} f(t_n), \quad (1)$$

where  $(I, Q)$  is a complex number,  $t_n = t_0 + n(5 T_{RF}/7)$  is the time at the  $n^{th}$  tick of the sampling clock,  $T_{RF} = 1/f_{RF}$ ,  $f(t_n)$  is value of the digitized waveform at  $t_n$ , and where  $\omega_{RF} = 2\pi f_{RF}$ .

$$(I, Q) = e^{-i\delta} \sum_n e^{-i2\pi 5n/7} f(t_n), \quad (2)$$

where  $\delta = 2\pi\omega_{RF}t_0$ . Because phase shifts of integer multiples of  $2\pi$  are not observable, the important part of  $\omega_{RF}t_n$  is  $\text{mod}(5n, 7)$ , the remainder of  $5n$  with respect to 7. The third plot on the page shows how  $\text{mod}(5n, 7)$  varies as a function of  $t_n$ . After 7 ticks of the sampling clock, corresponding to 5 RF cycles, the phase of the exponential is back in phase with the RF frequency.

In short, the down conversion process does a bin by bin multiplication of the second histogram by an exponential with the phase of the third histogram.

### 3 Explaining the Pattern

On the Echotek board, the sampling clock is derived from the Tevatron RF frequency and runs free. The sampling clock comes back in phase with the RF frequency every 5 RF cycles. The period of the Tevatron is 1113 buckets, which is not evenly divisible by 5. Echotek measurements are triggered by the turn marker. Consider the case that, at the marker for one turn, the sampling clock is in phase with the RF frequency, as is drawn in Figure 2. At the marker for the second turn, the sampling clock will be in its fifth state and the argument of the exponential will be shifted by  $6/7$  of  $2\pi$ . This can be seen by looking at  $t=3$  in the third plot in Figure 2. Therefore, if the Echotek board makes a measurement starting at the marker for first turn, and another measurement starting at the marker for the second turn, the two measurements will differ by a phase shift of  $12\pi/7$ . So long as all four BPM cables have the same phase shift the BPM will produce the same results for the position and intensity of both protons and Pbars.

On the marker for the start of the third turn, the sampling clock will be in its second state, which gives rise to an overall phase shift of  $5/7$  of  $2\pi$  relative to the first measurement. At the markers for the start of the fourth and fifth turns, the sampling clock will be in its sixth and third states, respectively. This gives rise to phase shifts of  $4/7$  and  $3/7$  of  $2\pi$ , respectively. Finally, at the start of the fifth turn, the sampling clock will in its first state and back in phase with the first measurement.<sup>1</sup> This cycle will then repeat.

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<sup>1</sup>Presumably the Echotek board is careful with race condition which occurs each time that the RF and sampling clocks come back in phase.

In summary, the phase of the (I,Q) measurement on a cable depends on the phase of the sampling clock at the turn marker which starts of the measurement. There are 5 possible values for this phase: the allowed values are  $0/7$ ,  $3/7$ ,  $4/7$ ,  $5/7$  and  $6/7$  of  $2\pi$ .

In the present Echotek boards, the command to arm for a measurement is controlled by the data logger which is not synchronized the beam. Therefore any group of measurements should sample all of the allowed 5 phases. This is consistent with the patterns observed on all four cables in Figure 1.

## 4 Explaining the Bad Data

In the data taken before March 5, 2004, the Pbar channels had an additional delay, relative to the proton channels, of 3 ticks of the  $7/5$  sampling clock. The effect of this delay can be understood by comparing the last two plots in Figure 2. The third figure has been described previously and the last figure shows the same sequence of phases, delayed by 3 ticks of the sampling clock.

For measurements starting at  $t=0$ , 1 or 2 the phase of the exponential is shifted by  $+2\pi/7$ , relative to the third plot. But, for measurements starting at  $t=3$  or  $t=4$ , the phase of the exponential is shifted by  $-2\pi/7$  relative to the third plot. Note the sign difference. This explains the empirical observation that the phase difference between the proton and Pbar cables had two stable values, separated by  $4\pi/7$ . When this offset was corrected in software the instrument reported sensible positions. An constant phase shift between the proton and antiproton cables does not affect the operation of the instrument so only one correction was necessary.

# Detail for Protons Only

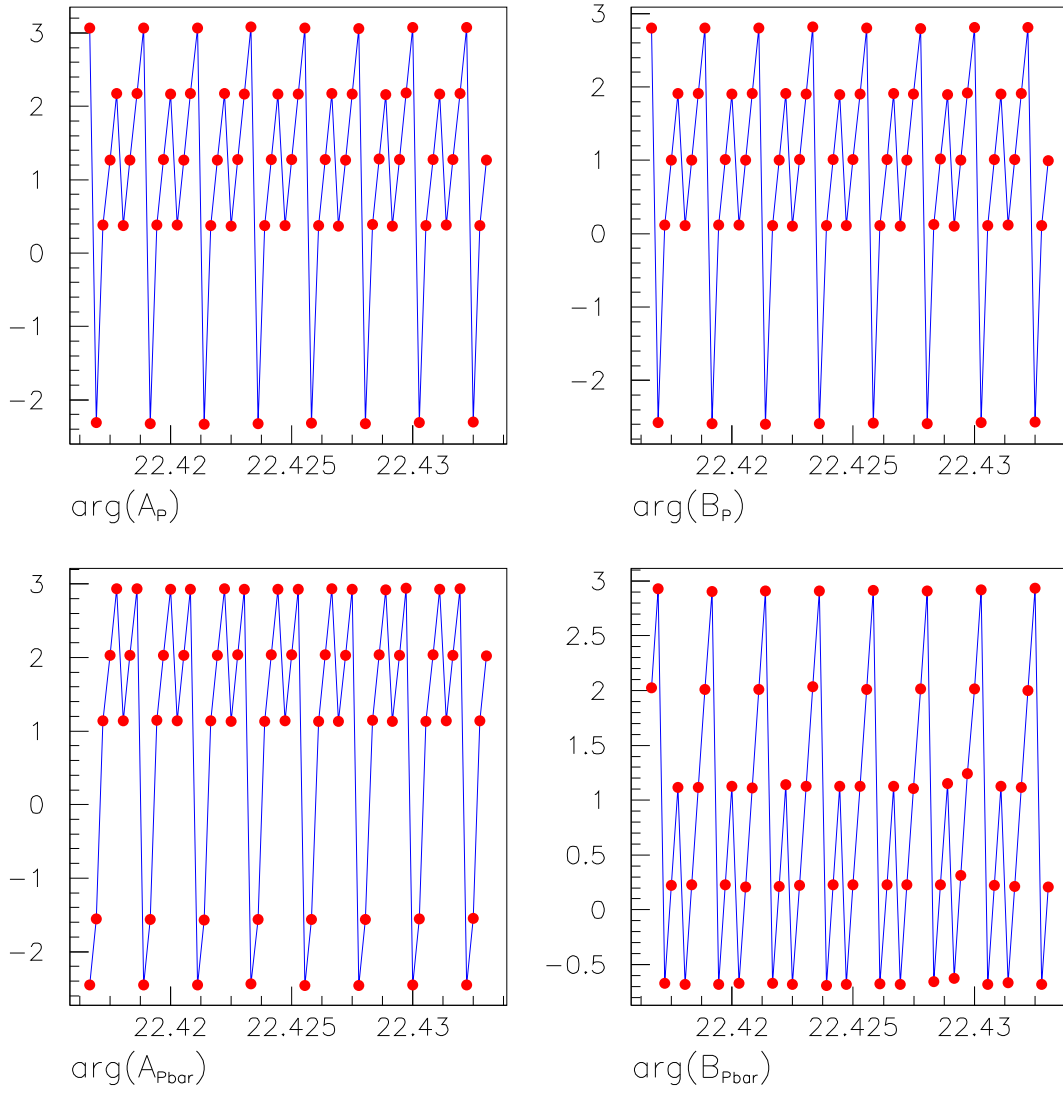


Figure 1: Plots for HA15 for the data of Mar 5, 2004. The plots show the phases of the signals on the 4 cables. For each cable, the phase has 5 possible allowed values.

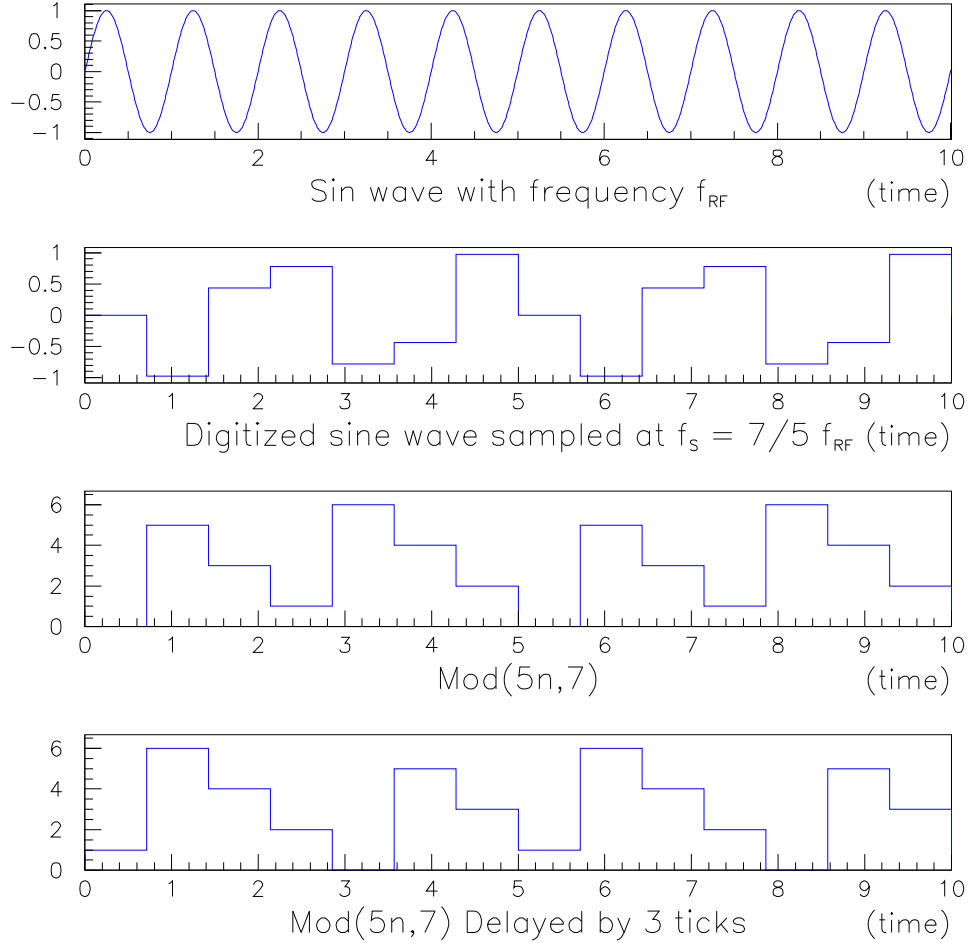


Figure 2: The first three plots used to illustrate the allowed and forbidden phases. The last plot is used to illustrate the effect of the extra delay which was present on the Pbar cables before March 5, 2004. In all plots the horizontal axis is time in units where the RF frequency is 1. The number  $n$  counts the number of ticks of the sampling clock. The plots are discussed in detail in the text.